

NEUTRON CAPTURES AND THE R-PROCESS

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The r-process involves neutron-rich nuclei far off stability for which no experimental cross sections are known. Therefore, one has to rely on theory. The difficulties in the predictions are briefly addressed. To investigate the impact of altered rates, a comparison of r-process production in hot bubble models with largely varied rates is shown. Due to the (n,γ) - (γ,n) equilibrium established at the onset of the r-process, only late-time neutron captures are important which mainly modify the abundances around the third r-process peak.

1. Introduction

Nucleosynthesis of elements beyond the iron peak requires reactions with neutrons due to the high Coulomb barriers which prevent charged particle reactions. Except for the relatively underabundant proton-rich p-nuclei, two processes have been identified for the production of intermediate and heavy nuclei: the slow neutron-capture process (s-process) and the rapid neutron-capture process (r-process). With neutron number densities around 10^8 cm^{-3} and low effective neutron energies of around 30 keV, the s-process synthesizes nuclei along the line of stability as the neutron captures are generally slower than all beta-decays encountered along its path (with the exception of several branching points where the two timescales become similar). Approximately half of the intermediate and heavy elements are created in the much faster r-process with neutron number densities exceeding 10^{22} cm^{-3} , effective neutron energies around 100 keV, and much shorter process times of up to a few seconds. These conditions point to an explosive site but the actual site has yet to be identified. The long favored idea of a high-entropy bubble in the neutrino wind ejected from a type II supernova shows persistent problems in explaining production across the full mass range of r-nuclei. Furthermore, there are indications that there must be two distinct sites ejecting r-process material at different frequencies (see

other contributions in this volume). In consequence, most r-process investigations focus on simplified, parameterized models which allow to study the required conditions and their sensitivities to nuclear inputs.

Due to the high neutron densities the r-process synthesizes very neutron-rich nuclei far off stability which subsequently decay to stability when the process ceases due to lack of neutrons or low temperatures. This raises the question whether we can predict reactions far off stability sufficiently well to make statements about r-process conditions. In the following two main topics are briefly addressed: The difficulties in predicting neutron captures far off stability, and the impact of neutron captures on the resulting r-process abundances.

2. Predicting Neutron Capture

As the astrophysical reaction rate is obtained by folding the energy-dependent cross section with the Maxwell-Boltzmann velocity distribution of the projectiles, the relevant energy window for neutrons is given by the location $E_0 \approx 0.172T_9(\ell + 1/2)$ [MeV] and width $\Delta \approx 0.194T_9(\ell + 1/2)^{1/2}$ [MeV] of the maximum of the Maxwell-Boltzmann distribution at the given stellar temperature. Since the cross section is integrated over this energy window, the available number of levels within determines the dominating reaction mechanisms. With a sufficient number of overlapping resonances (about 10) the statistical model (Hauser-Feshbach) can be used which employs averaged transmission coefficients and describes the reaction proceeding via a compound nucleus [1]. Single, strong resonances destroy the notion of the simple energy window as the integrand is split in several terms. Finally, in between resonances or without resonances, direct capture will become important. The temperatures above which the statistical model is applicable for the calculation of neutron- and charged-particle induced reaction rates have been estimated in [2]. Explicit limits are given in the global calculation of statistical model rates of [1]. These limits should be taken as a guideline when applying the rates given therein. Fig. 1 shows how direct capture becomes more and more important for nuclei with lower and lower neutron separation energy.

Basically, there are three groups of problems connected to the prediction of rates far from stability. The first two (partially overlapping) groups concern the difficulty in predicting nuclear properties relevant for Hauser-Feshbach and direct capture. For more details on these, see, e.g., [3]. Here, only the most important topics are outlined.

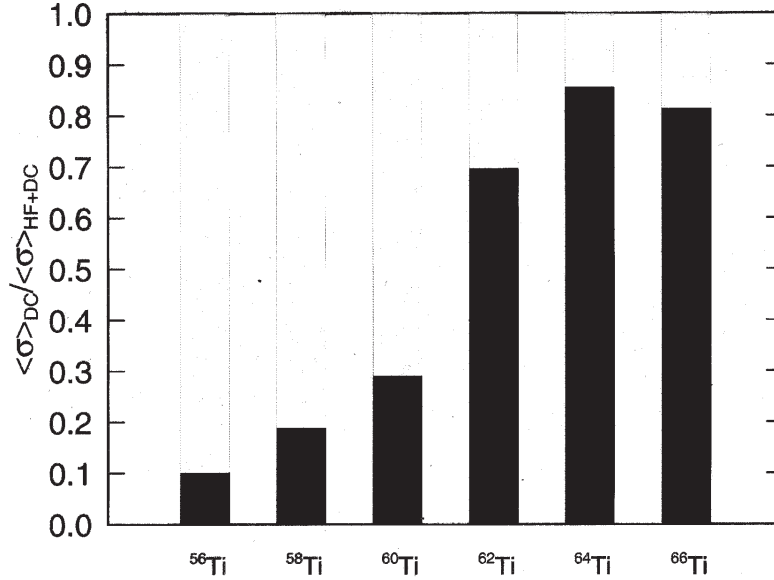


Figure 1. Portion of direct capture in the (n,γ) cross section for a series of Ti isotopes from a comparison of Hauser-Feshbach and DC calculations. Clearly, the DC contribution increases with decreasing neutron separation energy.

Direct capture calculations are extremely sensitive to the nuclear input, such as neutron separation energies, spins, parities and excitation energy of low-lying states, and the potential used in the neutron channel [4]. One of the largest problems is the determination of the spectroscopic factor which is difficult to calculate. At stability it is usually derived from (d,p) data. However, even there a considerable uncertainty is involved as it is taken from a comparison of prediction and data and thus is not independent of theory.

Due to the nature of the statistical model and its use of average quantities its sensitivity to most nuclear inputs is not as extreme as in the direct capture case. Nevertheless, it is yet uncertain how well the relevant nuclear properties, such as the particle separation energies, neutron optical potential, level density, and the low-energy tail of the GDR, can be described far off stability. Global models, in which the properties are not optimized to a few nuclei or a single mass region but rather are attempted to be consistently predicted for all nuclei, fare very well along stability. However, since the used descriptions are derived from data at stability (by either adjusting phenomenological or microscopic parameters) it remains

an interesting question whether they are still valid far off stability. Nevertheless, as pointed out above, the statistical model is not applicable at low neutron separation energies and therefore the impact of the uncertainties far off stability are limited.

The third problem is the identification of the dominant reaction mechanism and the interplay of different reaction mechanisms when their contributions are of similar size. Clearly, more work has to be done on this in the future. Lacking other data, basically all astrophysical investigations use Hauser-Feshbach rates even for isotopes where it is not applicable. With a low level density it is usually expected that the statistical model overestimates the actual cross section, unless strong, wide resonances are found in the relevant energy window.

3. Implementation of Neutron Capture in the r-Process

3.1. General

Given the difficulties in predicting rates far off stability, one might wonder whether it is possible at all to study the r-process, even if one resorts to simply parameterized networks. However, the situation is not that bad since it is not necessary to know the rates directly in the r-process path. Contrary to a sometimes still persisting misconception, the formation of r-isotopes *cannot* be viewed as occurring by a sequence of neutron captures until reaching an isotope with a β -lifetime shorter than the neutron-capture lifetime, somewhat like an s-process but moving further out from stability. As shown in Fig. 2, all neutron captures and photodisintegrations occur faster by several orders of magnitude than any β -decay in a given isotopic chain. In fact, the reactions are so fast that almost instantaneously ($< 10^{-8}$ s) an equilibrium state is reached in which the abundance Y for each isotope is determined by the balance of the reactions creating and destroying it: $r_{(n,\gamma)}Y_A = r_{(\gamma,n)}Y_{A+1}$. Since the two rates are related by detailed balance, the cross sections cancel out and the ratio is mainly depending on S_n , T , and ρ . Neutron captures will only start to matter during freeze-out when the lifetimes become longer due to lower temperatures and lower neutron number densities. It has been shown that the freeze-out proceeds very quickly for realistic conditions [5]. On one hand this limits the importance of neutron captures, on the other hand it validates the investigations which were performed using approximations such as instantaneous freeze-out [6].

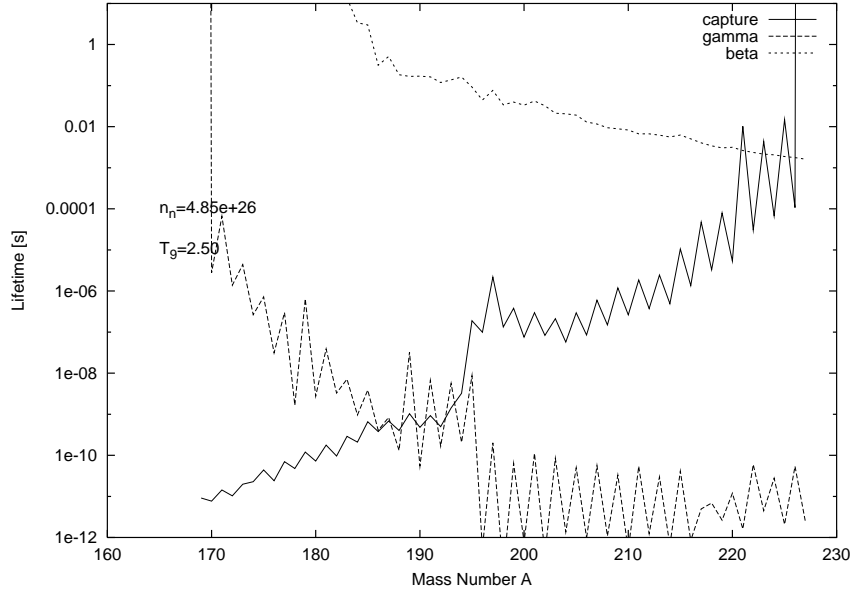


Figure 2. Lifetimes against (n,γ) (full line), (γ,n) (dashed), and β -decay (dotted) of neutron-rich Tm isotopes. Captures and photodisintegrations are much faster than β -decays and abundances are determined by an (n,γ) - (γ,n) equilibrium. (Lifetimes at the edges of the considered chain have been set to high values to prevent mass loss from the network.)

3.2. Dynamic *r*-process simulations

In order to study neutron captures in the freeze-out it is necessary to perform dynamic *r*-process simulations. As an example, calculations in the model of an adiabatically expanding hot bubble were performed, similar to [5] but with updated, temperature-dependent rates, including the theoretical rates of [1]. In this model of a primary *r*-process, a blob of matter at high temperature ($T_9 \approx 9$) expands and cools. For the calculations here the same expansion was chosen as used by [5] in their case of 50 ms expansion timescale. Due to the initial high temperature, all reactions, including charged-particle reactions, are in equilibrium and the resulting abundances can be calculated for each temperature from the equations describing a full NSE. The charged-particle reactions, in particular the α captures, cease at around $T_9 \approx 2.5$. Below that temperature it is not necessary to use a full network but one can utilize a simpler network, only including (n,γ) , (γ,n) , and β -decays. The seed abundances for this *r*-process network are given

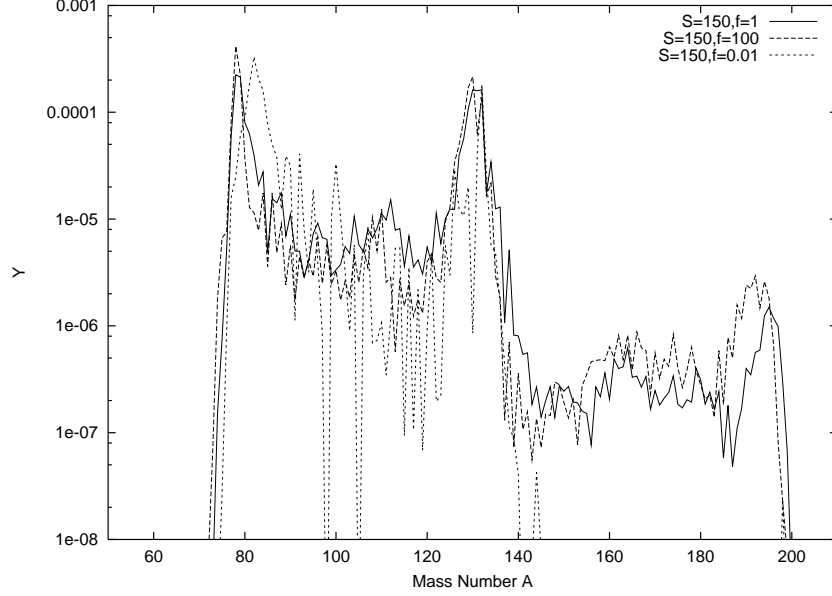


Figure 3. Decayed final abundances of the $S = 150$ models. The neutron rates were multiplied by factors 1.0 (full line), 100. (dashed), and 0.01 (dotted), respectively.

by the freeze-out abundances of the charged particle network. More specifically, depending on the freeze-out conditions the slow triple- α rate will either be able to convert all α 's to heavy mass nuclei or it will be too slow, leaving a certain α mass fraction. The latter is called α -rich freeze-out. The process conditions are specified by the entropy S , the electron abundance Y_e , and the expansion timescale. Depending on the conditions, more or less free neutrons per heavy seed nucleus are available after the charge-particle freeze-out. Due to the still high temperature an (n, γ) - (γ, n) equilibrium is established. The β -half-life of the most abundant nuclei in each isotopic chain (these are only one or two due to the shape of the equilibrium equation) determine how fast material can be converted to the next element. Each chain remains in equilibrium until finally the r-process freezes out.

For this comparative study, representative seed abundances were chosen without following the full charged particle network. The calculations always started by only populating the Fe chain but with realistic Y_n/Y_{seed} and Y_α (depending on entropy and Y_e) taken from parameterized results of full calculations. Since the uncertainties in the neutron capture rates might be large, for two entropies 3 exemplary cases are shown here: with standard

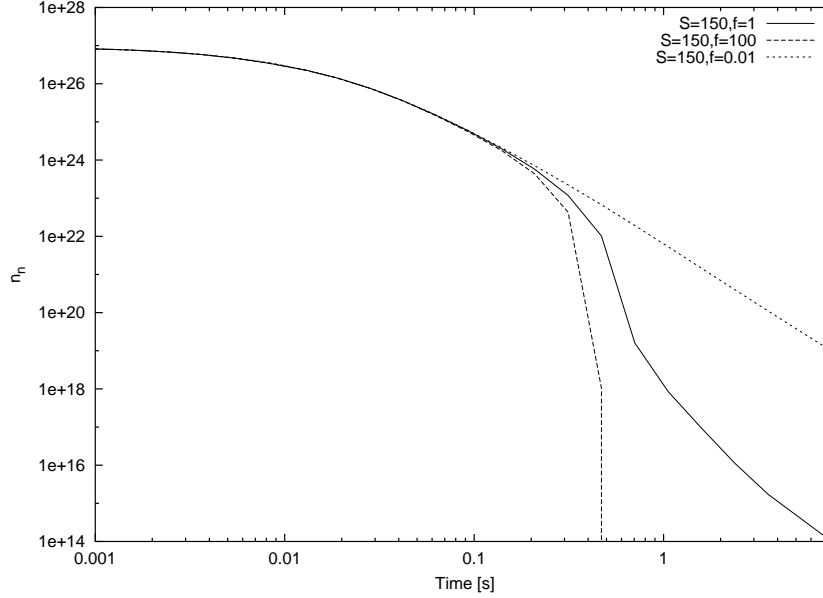


Figure 4. Time evolution of the neutron number density in the $S = 150$ models. The neutron rates were multiplied by factors 1.0 (full line), 100. (dashed), and 0.01 (dotted), respectively.

rates and with neutron captures multiplied by a factor of 100 and a factor of 0.01, respectively (this implies that the photodisintegrations are changed by the same factor). Figs. 3 and 5 show the final abundances, the neutron number densities as a function of time are shown in Figs. 4, 6. At low entropy there are not enough free neutrons to considerably change the seed abundance, the neutron freeze-out is also fast. It was already shown in [5] that the freeze-out at higher entropy is slower and that final neutron captures can alter the resulting abundances of heavy nuclei but not of light ones. The trough before the high-mass peak was filled by late neutron captures.

The freeze-out behavior obtained here depends on the chosen neutron rates. The time at which the n_n for the three cases diverge indicates the fall-out from the rate equilibrium. After this point it depends on the entropy how far up in mass nuclei have been produced and on the neutron captures how their abundances are altered. As can be seen in Figs. 4 and 6, the final freeze-out phase is faster for larger rates. This reflects the increased capture when the forward and reverse rates fall out of equilibrium which uses up

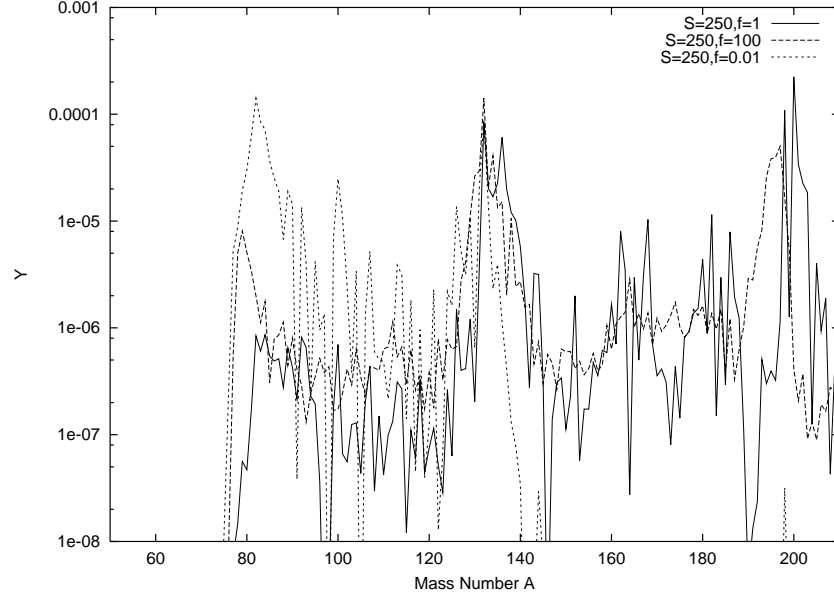


Figure 5. Decayed final abundances of the $S = 250$ models. The neutron rates were multiplied by factors 1.0 (full line), 100. (dashed), and 0.01 (dotted), respectively.

neutrons faster. The masses above about 140 are mainly produced in this late freeze-out phase and are therefore more sensitive to the value of the neutron captures. Especially in the high entropy case shown in Fig. 5 it is evident that faster neutron captures smooth the abundance distribution and fill the trough before the $A \approx 200$ peak. For both entropies, the artificially suppressed rates do not allow to build up considerable abundances beyond $A \approx 140$.

4. Conclusion

The simple comparison shown above for the hot bubble model has to be interpreted cautiously. Despite the fact that there might be considerable uncertainties in the theoretical rates far off stability changing *all* rates in a range of 4 orders of magnitude seems unrealistic. Even if new effects (like pygmy resonances [7] or overestimated cross sections [3]) might change the rates by factors of 10 for extremely neutron-rich nuclei, late-time captures will not include such nuclei but will occur closer to stability. Moreover, for reproducing the solar r-process pattern it is necessary to superpose a number of components with different entropies. Thus, effects of rates

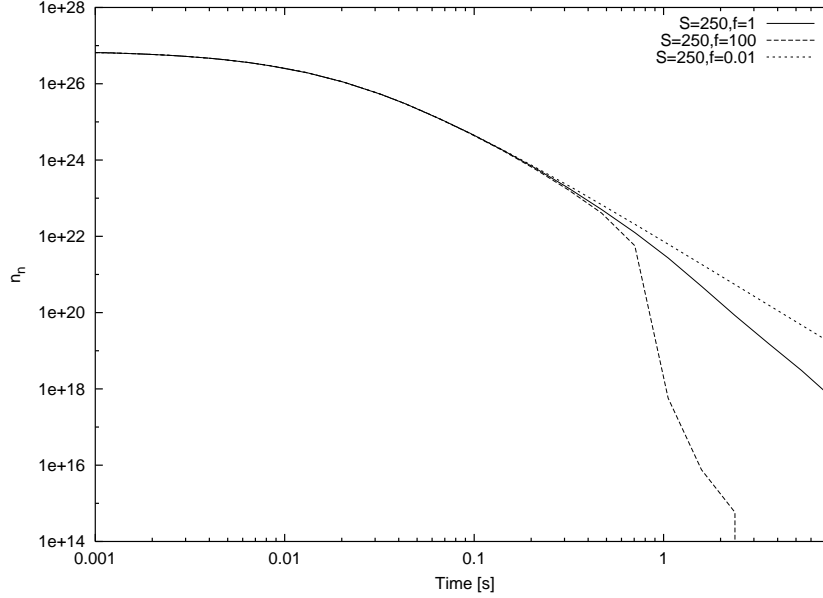


Figure 6. Time evolution of the neutron number density in the $S = 250$ models. The neutron rates were multiplied by factors 1.0 (full line), 100. (dashed), and 0.01 (dotted), respectively.

altered on a large scale, as shown above, can be compensated by a scaling in entropy and a different weight distribution. Thirdly, a more realistic seed abundance distribution might also decrease the difference in heavy element production between the different cases. Higher entropies realistically start with seed abundances in the $A \approx 110$ region and require less neutrons to form more heavy elements. However, this was not taken into account here to purely show the influence of altered neutron captures.

Despite the above caveats the main conclusions are consistent with other studies [5,8]. Components with high entropy freeze out slower and late-time neutron captures can modify the final abundance distribution mainly in the region $A > 140$. Therefore, emphasis has to be put on improving the prediction of nuclear cross sections and astrophysical reaction rates in that mass region.

Acknowledgments

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